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AND THE

ABSORPTION THEORY

AN ACCOUNT OF THE PRINCIPLES OF THE MODERN SEWAGE FILTER

BY

F. WALLIS STODDART, F.I.C., F.C.S.

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BRISTOL:
JOHN WRIGHT & SONS LTD., PRINTERS, STONE BRIDGE
1911

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NITRIFICATION AND THE ABSORPTION THEORY.

By F. Wallis Stoddart, F.I.C., F.C.S.

The evil effects on practical sewage disposal of too hasty generalization from experiments on the laboratory scale have been so frequently demonstrated, that there has, until recently, been a tendency to overlook the equally obvious fact that a true understanding of the complicated phenomena involved can only be built up step by step from the results of artificial experiments upon simpler materials, in which the varying factors can be controlled, and which can be repeated at will by independent observers.

During the last few years this has been recognized by several investigators from whose laboratories have emanated researches of the greatest value; and it is hoped that the present contribution, which summarizes experiments that have been carried on continuously for upwards of twenty-five years, will fulfil a similar purpose, namely, to put on record certain facts in connection with nitrification which must be taken into account in designing means of bringing about biological oxidation; and which may, in association with the work of others, help towards the comprehension of the complex changes occurring in sewage purification.

The primary object of these experiments is to ascertain the manner in which the process of nitrification can be brought to the highest degree of activity, and the extent to which it is affected by conditions such as temperature and concentration which occur naturally in the course of sewage treatment.

An inclination has been shown recently, especially by those investigators who attribute a chief share in sewage purification to physical agencies, to belittle the practical importance of nitrification.

The evidence, however, is overwhelming that, useful as the preliminary partition of sewage constituents may be, the final disposal of the putrescible matters is entirely the work of living organisms, and, in the main, of bacteria; and further, that this is especially true of the soluble impurities contained in the clarified sewage which is more particularly the seat of the process of nitrification.

The importance of this change lies not so much in the fact that its incidence fixes in an innocuous form that element which is most characteristic of unstable and putrescent matters, as in the close analogy it bears to parallel processes of oxidation by which all the sewage products offensive to the senses are converted into unobjectionable saline matters.

The method of investigation was essentially identical with that previously described by the writer in 1893 (1), namely, a constant trickle of an ammoniacal solution over a column of air-charged medium, rendered active by seeding from a culture of the oxidizing organisms. It is a little surprising that this method has not been followed by later investigators, who have almost without exception adopted the flask method of cultivation, in which the air supply must necessarily be defective; and in many cases the solutions employed have been unnecessarily complicated, so that the experiments have been wanting in that simplicity which is demanded. Almost the only systematic investigation in which the method of continuous flow has been followed is that recorded by Dr. Harriette Chick (2): but in this case the fluid applied was clarified sewage with its wide variations in composition, and the mode of application of the liquid was not truly continuous or uniform in character; her results, therefore, are not strictly comparable with those now detailed.

The apparatus employed consisted of a vertical tube charged with graded medium to which the ammoniacal solution is applied by means of a dropper fed from a "bird-fountain" reservoir ensuring a constant head. (*See Plate.*)

By varying the diameter of the orifice of the dropper the flow of liquid can be adjusted to any desired rate, and the fountain reservoir enables one to maintain this rate unaltered for as long a period as may be necessary.

The composition of the medium is a matter of some importance for the reason that whilst the base necessary to satisfy the nitric acid formed is readily supplied in solution for the higher dilutions such as are met with in sewage, this is not the case with the more concentrated solutions containing upwards of 50 parts of ammoniacal nitrogen per 100,000, especially as the best results are obtained when calcium carbonate is used for this purpose.

The gradual destruction of the medium is the chief objection to the use of a soluble material, but as it is not attacked until the dissolved bases are exhausted, this objection does not carry much weight in dealing with the higher dilutions.

Several bye-problems of great interest and importance can be satisfactorily investigated only by the use of filters composed of some perfectly stable medium such as silica; numerous experiments of this kind are in hand, but are outside the scope of the present communication.

In order, therefore, to bring all the experiments here recorded into line, the medium in every instance has been white marble broken into fragments as nearly as possible of uniform size, namely, one-eighth of an inch; and has been prepared by collecting only that portion which is passed by a sieve of six meshes and retained by one of eight meshes to the inch. A cubic yard of such material presents a superficial area of 900 sq. yards.

The filter, or nitrifier, consists then of a glass tube of one inch internal diameter filled to a depth of exactly three feet with this medium, which is held in place by one or two larger fragments of marble.

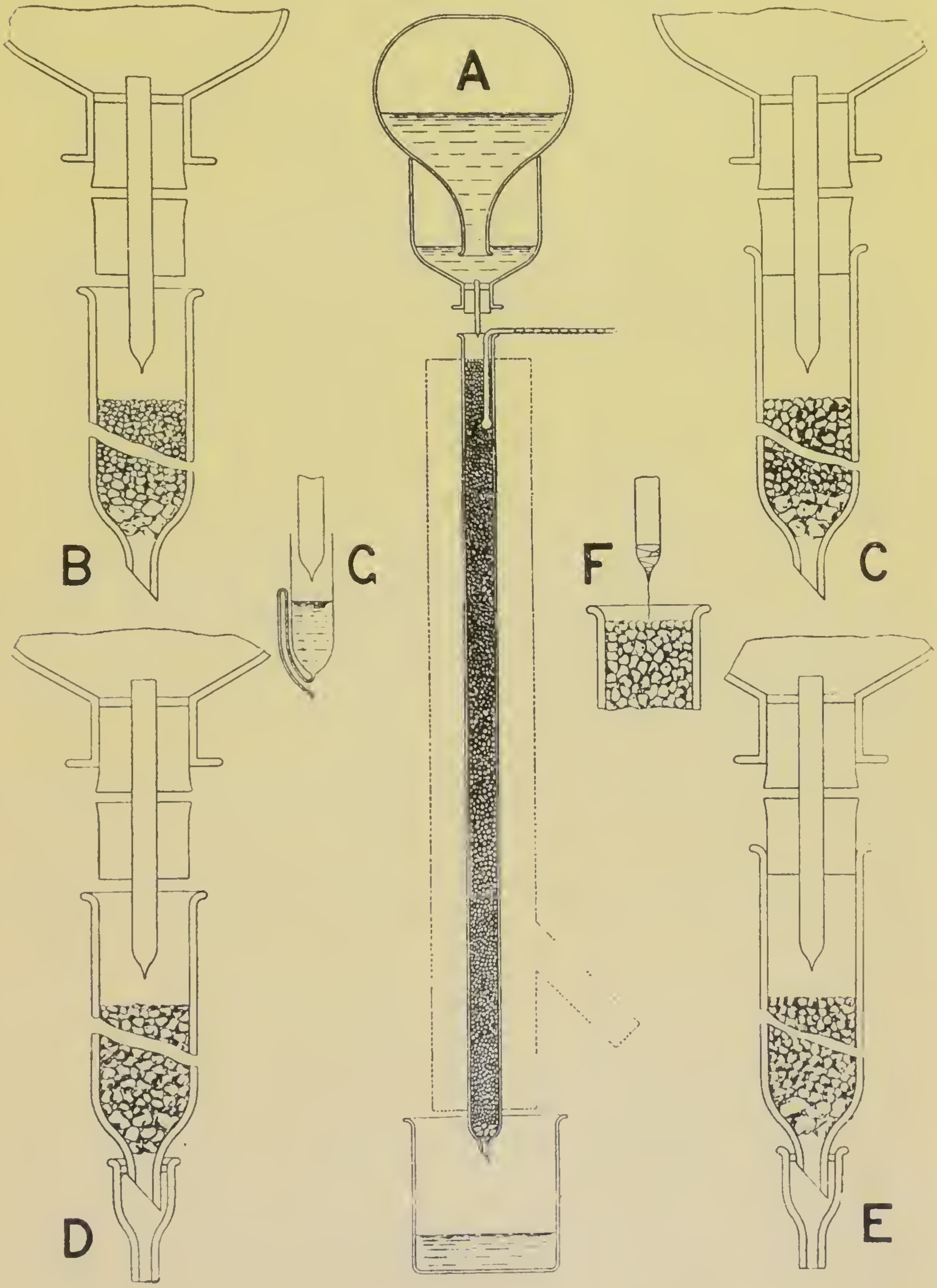
The lower end of the tube is drawn out and cut off obliquely for a reason that will shortly appear.

The internal capacity of three feet of empty tube is 455 c.c., the space occupied by medium is 245 c.c.. and the interstitial capacity when filled 210 c.c. As it is convenient to have a short length of tube above the medium, the entire air capacity of the filter ready for use is 255 c.c.

The filter so prepared is seeded with a little pasty chalk from a stock flask culture of the nitrifying organisms diffused in water; it is then fed in the manner described with gradually increasing quantities of ammonia, until maturity is reached.

As a variety of dilutions are required, it is well to make a stock solution of ammonia containing one per cent. of nitrogen, from which the appropriate dilutions are readily prepared, each c.c. of stock solution per litre representing one part of nitrogen per 100,000.

CONTINUOUS NITRIFIER.



In making up the stock solution any ammonium salt may be used, but it may be pointed out that the carbonate requires only half the quantity of base demanded by the sulphate or chloride, but is rather more difficult to maintain at constant strength, whilst the alkalinity of the more concentrated solutions may impair the activity of the organisms; further, that the sulphate when concentrated sometimes embarrasses the filter owing to the formation of crystallized calcic sulphate, and that on the whole the chloride serves the purpose best.

The necessary quantity of the salt is dissolved in water together with sodium ammonium phosphate at the rate of 0·2 gramme per litre, boiled, allowed to cool, rendered slightly alkaline with sodium carbonate, and then adjusted to strength.

For dilution a pure hard water is suitable; in these experiments the Bristol public supply, which is practically destitute of ammonia, and contains in solution very constantly 20 parts of calcium carbonate per 100,000, was employed.

No further complications are necessary or advisable.

With reference to the methods of analysis employed, ammonia and nitric acid were estimated by the usual means, that is to say, reduction of the latter to ammonia by means of the copper-zinc couple, and determination of the ammonia in both cases by distillation and nesslerisation.

The chief weakness here lies in the inherent defects of a colorimetric comparison. Very considerable accuracy is attainable in the case of the higher dilutions in this way, but in the more concentrated solutions the multiplication of experimental error—generally on the side of loss—makes agreement more difficult, and this probably accounts for an apparent loss of nitrogen during the process of nitrification.

Nitrous acid when present was determined by a permanganate method which presents several advantages in the absence of other reducing bodies, the presence of which—as, for instance, in sewage—would of course invalidate its use.

The standard solution is prepared by dissolving ·4515 gram potassium permanganate in a litre of water.

Each c.c. then represents ·1 mgrm. nitrous nitrogen.

The manipulation is exactly as in the "oxygen absorbed" test, except that the operations are carried out at ordinary temperatures, and without delay.

All analytical results are recorded, unless otherwise stated, in parts per 100,000; and the contraction C.Y.D. means per cubic yard per day of 24 hours.

I.—Aëration of the Filter. Table A.

The first experiments to be described were directed to ascertain the mode of replenishment of oxygen.

In order to determine whether lateral aëration was advantageous or not, perforated tubes were used side by side with the glass tubes described above.

A tube made of perforated zinc was very unsatisfactory; the medium contained in it was very slow in becoming active, and never reached a high potency. As it was suspected that the metallic zinc might be concerned in this, and as a small quantity of zinc (0·2 part per 100,000) was actually found in solution in the filtrate, a tube was constructed of parallel glass rods kept apart by small rubber rings, and bound together round three short sections of glass tube. This filter ripened normally, TABLE A.

STUDIES IN NITRIFICATION.

AËRATION OF FILTER.

Strength of Solution, 5 parts Nitrogen per 100,000; Rate of Flow, 520 gallons per C.Y.D.; Temperature, 5° C.

Arrangement of Filter	Normal	Dripper connected with Medium	Closed at Top	Closed at Bottom	Closed at Top and Bottom	Normal
Ammoniacal Nitrogen	·89	·77	2·47	2·45	4·45	·90
Nitrous Nitrogen	·03	·04	·04	·01	·02	·02
Nitric Nitrogen	3·80	4·08	2·26	2·46	·47	3·85
Percentage of Nitrogen recovered as—						
Ammonia	19·8	15·4	49·4	49·0	89·0	18·0
Nitrous Acid	·6	·8	·8	·2	·4	·4
Nitric Acid...	76·0	81·6	45·2	49·2	9·4	77·0
	96·4	97·8	95·4	98·4	98·8	95·4

but never quite attained the activity of the closed filters, a fact probably due to the desiccation of the peripheral medium, and the consequent confining of the solution to a central column.

As no improvement was effected by either device, all the subsequent experiments were conducted with tubes communicating with the air only at top and bottom.

One such filter then was selected and kept steadily at work until it was found to have attained its maximum power—(Table A, Col. 2)—and the following modifications were made. (*See page* 7.)

(*a*). In order to ascertain if the actual division of the liquid into drops had any influence, the dropper was directly connected with the medium by a short length of thread or platinum wire—(Plate, fig. F)—so that there was complete continuity of the liquid throughout its whole course from reservoir to receiver. The results recorded in Col. 3 show that no appreciable effect was produced.

(*b*). A rubber bung fitting the top of the filter tube was then passed on to the dropper, and forced into the former, so as to hermetically seal it. (Plate, fig. C.)

The results given in Col. 4 show that the oxidation was seriously curtailed owing to the diminished oxygen supply.

(*c*). The bung was then removed, and the lower end of the filter tube sealed by attaching an adapter with the end cut off square. (Plate, fig. D.)

Under these circumstances a drop of liquid lodges in the end of the adapter, and in this way access of air to the filter from below is effectually prevented without impeding the flow. The effect (Col. 5) was very similar to that of the previous experiment.

(*d*). The filter was then sealed at top and bottom, as in (*a*) and (*b*). (Plate, fig. E.)

With the total exclusion of air liquid begins almost immediately to collect in the receiver, owing to diminished internal pressure, until at the end of an hour about 15 c.c. have accumulated; at this stage the filtrate contains but little nitrate or nitrite (Col. 6), and the former soon disappears entirely, the liquid then passing through the system almost unchanged. Unless, however, special precautions are taken to keep the liquid free from dissolved oxygen, there is always some nitrite in the filtrate.

(*e*). Lastly, the tube was restored to its original condition—(Plate, fig. B)—when the filter promptly resumed its full powers, and nitrification was soon completely re-established. (Col. 7.)

It is evident from these experiments that the current theories as to the mode of renewal of oxygen in continuous filters need revision.

One view, negatived by experiment (*a*) is that air is introduced from above by the "injector action" of the drops.

A second is that by some unexplained agency an upward convection current is maintained. Apart from the fact that no intelligible explanation of the mechanism of this up-draught has been offered, this suggestion is disproved by experiments (*b*) and (*c*), in which all possibility of such a movement is destroyed by the seal at top or bottom; also by an arrangement similar to (*b*), but in which the rubber bung is replaced by a fairly tight stopper of cotton-wool. Whilst this prevents a convection current, it cannot check the entrance of air due to diminished internal pressure, and the action of the filter is quite normal.

The replenishment of oxygen is plainly due to the partial vacuum produced by the fixation of oxygen as nitric acid, and equalization by diffusion.

In fact, the process may fairly be described as one of continued inspiration, the necessity for an expiration being obviated by the fact that the oxidation product is excreted in solution.

Experiment (*a*) shows also that the actual sub-division into drops is not essential, and that the liquid may be delivered in fine streams, provided that these are not sufficiently copious to waterlog the medium, a conclusion entirely corroborated by later experiments under Section III., in which the liquid is actually fed in streams and not in drops.

II.—EFFECT OF INTERRUPTION OF FLOW. TABLE B.

So much stress has been laid upon the importance of intermission of flow and of periods of rest, that it seemed worth while to make a direct comparison of the continuous and intermittent methods under otherwise identical conditions.

This was effected by causing the dropper, which in this case delivered at the rate of 585 gallons per C.Y.D., to discharge at will into a small reservoir fitted with a syphon (Plate, fig. G). By varying the capacity of the reservoir, the interval between the discharges could be adjusted as desired.

The results are given in Table B.

TABLE B. STUDIES IN NITRIFICATION.

EFFECT OF INTERRUPTED FLOW.

Strength of Solution, 10 parts Nitrogen per 100,000; Rate of Flow, 585 gallons per C.Y.D.; Temperature, 22° C.

Feed	Continuous	Intermittent		
		10 minutes	1 hour	2 hours
Ammoniacal Nitrogen...	·85	1·05	3·38	5·52
Nitrous Nitrogen ...	·65	·47	·09	·40
Nitric Nitrogen ...	8·40	8·20	5·93	3·40

The progressively increasing imperfection of oxidation, noticeable with a period of ten minutes, becomes very marked as the intervals lengthen. That this effect is not in any way due to depreciation in the activity of the organisms owing to deprivation of nourishment is proved by the fact that the filter may be left idle for days, and yet will at once resume its full activity when treated with a continuous flow of ammoniacal solution; it is plainly the result of the excessive rate of flow at the periods of discharge.

So far then from assisting the action of the filter, the intermittent discharge, with its inevitable inequality of flow, reduces the efficiency very appreciably, and indeed produces an effect comparable with that of defective aëration. A completeness of oxidation equal to that attainable by a continuous flow can only be ensured by either reducing the volume of solution liberated at each discharge, or reducing the strength of the solution until it contains only such a proportion of nitrogen as can be oxidized at the maximum rate of flow; that is to say, by diminishing the work the filter has to do.

III.—Effect of Variation in Temperature. Table C.

In order to note the manner in which nitrification is affected by changes in temperature, the filter was surrounded by a water jacket heated by a small burner. The temperature noted was that recorded by a delicate thermometer, the bulb of which was buried in the medium at a depth of four inches from the surface. The changes were repeated several times in order to eliminate any differences in nitrifying power brought about by nursing the organisms at a possibly exceptionally favourable temperature; but as a matter of fact no evidence of any such intensifying effect was observed, the amount of nitrogen oxidized following the temperature with great regularity.

One noteworthy difference between high and low temperatures was this, that near the maximum point, if an excessive amount of ammonia were used, a marked exaggeration of nitrite formation resulted at the expense of nitrate; whilst at low temperatures, whatever the excess of ammonia might be—only traces of nitrite were present at any time.

It appears as if the nitric organisms were much more sensitive to adverse influences than the nitrous at the higher temperature.

Care was taken not to push this elevation of temperature to an extreme, and so to bring the experiment to a premature conclusion; the thermal death point, therefore, was not determined, but is probably much the same as for other non-sporing organisms.

The conclusion to be drawn from these experiments is that nitrification is markedly intensified by elevation of temperature up to about 30° C., beyond which it is adversely affected.

IV.—Effect of Variation in Strength and Rate of Flow. Table D.

In these experiments the object was to ascertain the maximum amounts of ammoniacal nitrogen that could be completely nitrified at different degrees of dilution.

Having prepared a series of droppers delivering at various rates, ranging from 50 to 10,000 gallons per square yard of surface in 24 hours, the strength of the solution was adjusted until the point was reached at which no ammonia or nitrite was detectable, but beyond which traces of one or both of these substances appeared.

Table D gives the essential results of these tests, and at the foot of each column is a statement of the weight of nitrogen oxidized in 24 hours by one cubic yard of medium.

The uniformity in these amounts is quite remarkable, and might possibly be still more striking if it had been possible to exercise a more perfect control over the temperature.

Table C.

Effect of Alterations in Temperature.

Strength of Solution. variable ; Rate of Flow uniform at 100 gallons per C.Y.D.

	Successive Days.												
Ammoniacal Nitrogen	None	1·37	2·92	8·0	14·7	5·3	·55	6·5	None	None	None	None	None
Nitrous Nitrogen	·05	2·0	3·9	3·1	2·1	3·8	·07	·08	·01	None	·80	·10	·10
Nitric Nitrogen	60·9	60·9	59·1	54·2	49·1	56·9	65·3	58·1	68·0	53·5	49·0	32·9	9·5
Total Nitrogen...	60·95	64·29	65·92	65·3	65·9	66·0	65·92	64·68	68·01	53·5	49·8	33·0	9·6
Ammoniacal Nitrogen in original solution	65	70	70	70	70	70	70	70	70	55	50	35	10
Temperature	29°C.	34°C.	37°C.	39°C.	33°C.	33°C.	31°C.	38°C.	30°C.	25°C.	20°C.	10°C.	0°C.
Grains Nitrogen fully oxidized per C.Y.D.	4263	4263	4137	3794	3437	3983	4571	4067	4760	3745	3430	2303	665

Table D.

STUDIES IN NITRIFICATION.

Effect of Varying Strength of Solution and Rate of Flow. Temperature, 20°—25° C.

Rate of Flow in Gallons per C.Y.D. ...	54	100	222	585	1,170	2.610	5.022	10.800
Ammoniacal Nitrogen...	None	None	None	None	None	None	None	None
Nitrous Nitrogen	None	None	None	None	None	None	None	None
Nitric Nitrogen	59·3	49·4	22·4	7·95	3·95	2·06	1·05	·52
Ammoniacal Nitrogen in original Solution	62·5	50	23	8·5	4·5	2·0	1·1	·5
Grains of Nitrogen oxidized per Cubic yd. of medium in 24 hours	2362·5	3500	3574	3510	3700	3654	3870	3780

There is a small but distinct increase in oxidizing power as the dilution increases, which may very reasonably be attributed to the larger proportion of solvent; the low value for the lowest rate of flow may be due in part to the failure of so scanty a trickle to moisten and utilize the whole of the medium.

As a broad statement, it will be a fair approximation to place the maximum amount of ammoniacal nitrogen, in ordinary dilutions and at ordinary temperatures, completely nitrifiable by one cubic yard of medium in 24 hours, at half a pound.

It is very difficult to gather from the results of other observers what they have effected in this direction; but as far as can be ascertained, the maximum work attained has been about one-third of this.

V.—THE EFFECT OF VARIATION IN FILTER DEPTH. TABLE D2.

So far all results have been recorded upon the true cubic yard of filtering material, that is a mass measuring three feet in each of all three dimensions.

If, however, the filter body be re-arranged so that the depth is increased at the expense of the superficial area, the efficiency is greatly enhanced. The following table shows the effect of this change when the depth is doubled in this way.

TABLE D2. STUDIES IN NITRIFICATION.

EFFECT OF DOUBLING THE DEPTH OF FILTER.

Temperature	15° C.		22° C.	
Depth of Filter in feet	3	6	3	6
Grains N. oxidized per C.Y.D. ...	2900	3675	3500	5468
Gain per cent		27		56

VI.—THE INFLUENCE OF HUMUS ON NITRIFICATION.

In his admirable researches on the oxidation of sewage recently published in a complete form by the Royal Commission on the Disposal of Sewage (3), Dr. Adeney suggests very strongly that whilst it is comparatively easy to induce nitrosification, or the formation of nitrite, in inorganic solutions, the presence of "humus," a stable solid residue of the complete oxidation of sewage, is absolutely necessary for the performance of the final change, the conversion of the nitrite into nitrate.

No support is given to this suggestion by the experiments already described. No organic substances of any kind were introduced with the solutions used, and no material that could be described as humus formed on the medium in the filter.

The records of Dr. Adeney's researches, carried out with a totally different object in view, do not afford information that would justify an attempt to explain how this impression can have arisen, and it is not possible to say more on the subject than that nitrification can apparently be effected in a remarkably complete manner without the intervention of humus.

VII.—The Absorption Theory.

Nor do these observations afford support to the theory of absorption which has of late attracted so much attention, and captured so many adherents under the able advocacy of Dr. Dunbar.

This hypothesis assumes that the dissolved oxidizable matter of sewage, when the latter is applied to a filter, is removed from solution and transferred to the solid medium or to the coating gradually formed upon it; and that subsequently, but at a considerable interval, and under the influence of the oxidizing organisms, it assumes a different chemical shape in which it is re-transferred to the liquid, and finally emerges in the filtrate.

The period occupied by these operations is variously stated to extend over days, weeks, months, or even years.

The foundations of the doctrine are very clearly enunciated by Dunbar (4) as follows:—

After referring to the rapidity with which dissolved salts and dyes pass through a filter, and to the fact that simultaneously the oxidized products of the original organic matters, and not those matters themselves, appear in the filtrate, Dunbar proceeds to recall the view of Frankland and others, "that the bacteria in the sewage and in the filter directly mineralized the organic matters during the slow flow of the sewage through the filter."

In a later section (5), referring to the writer's publications on this subject, it is stated quite correctly that "Stoddart shared the generally prevalent . . . view of land filtration," *i.e.*, that the soluble oxidizable constituents of the sewage are immediately oxidized by the micro-organisms during its passage over the particles of soil (or filtering medium). The argument then proceeds: "This was a possible explanation so long as it could be assumed that the sewage remained for about three days in the filter; but when it was shown that the sewage left a 3 feet filter thoroughly purified within ten minutes, and shallower filters in shorter periods, the above explanation fell to the ground. It cannot be assumed that micro-organisms decompose highly complex molecules of organic substances within a few minutes or seconds with the formation of ammonia and nitrogen gas, and oxidize these substances to nitric acid, organic carbon to carbonic acid, organic sulphur to sulphuric acid, etc. It can only be assumed that the *dissolved organic matters are first separated from the sewage during its passage through the filter, and are retained in the filter to be decomposed and oxidized by the micro-organisms during the succeeding period of rest.*" The italics are Dr. Dunbar's.

The explanation of this phenomenon is then discussed, and after dismissing mechanical filtration and chemical combination, Dunbar selects absorption as the only possible solution.

It is not perfectly clear on what substances, or classes of substances, absorption is exercised.

Initially the suggestion undoubtedly applied to organic colloids only (6), *i.e.*, soluble but non-dialysable bodies; but Dunbar himself extends the list to dialysable but absorbable substances such as peptone, colouring matters, and a variety of substances "of high molecular weight" (7).

Other adherents of this theory, influenced no doubt by the supposed analogy with soil action, have, possibly without Dunbar's concurrence, included also in the category of absorbable substances simpler compounds, such as ammonia.

Lastly, Dunbar associates all classes of sewage filters in this explanation (8).

Now it is extremely difficult to comprehend how in the case of the continuous filter, many examples of which have been in uninterrupted action for several years, absorption, which naturally implies a retardation in the delivery of the oxidized products, can play any essential part.

Indeed the reference to a period of rest in the italicised passage quoted above precludes any possibility of applying the theory to an appliance which enjoys no such relaxation, and which yet exhibits in an unequalled degree the power of oxidation.

The point is brought out more emphatically by so modifying the conditions of the preceding experiments as to directly compare the duration of passage of a simple salt, such as sodium chloride, with that of the oxidation and discharge of ammonia.

Two reservoirs and droppers are arranged to give the same rate of flow: one (A) is charged with water, and the other (B) with the solution under investigation.

A mature filter in active work is then thoroughly washed out with water, and the water dropper A applied and allowed to run until the rate of flow through the filter is uniform.

Reservoir B, charged with salt solution, is then substituted for A, and the filtrate tested at short intervals. In this way the first appearance of chloride, its gradual increase, and the attainment of maximum quantity are all noted without any interference with the rate of passage of the liquid through the filter. When the salt solution is coming through at full strength, the reservoirs are again interchanged, and the gradual disappearance of the chloride noted, and in this way a curve is obtained forming a record of the behaviour of a substance not affected in any way by the biological equipment of the filter.

The experiment is then repeated, reservoir B being now charged with ammoniacal solution of appropriate strength. As long as reservoir A is applied the filtrate shows no trace of nitrogenous compounds; either no ammonia remains "absorbed" from previous experiments, or it is so securely locked up as to be beyond the reach of the organisms. Shortly after the substitution of B for A, the precise time depending on the rate of flow, nitrate appears in the filtrate, and increases until the full amount corresponding to the ammonia introduced appears; then on replacing B by A the nitrate gradually disappears, and the times of appearance, of maximum, and of disappearance exactly correspond with those of the salt solution.

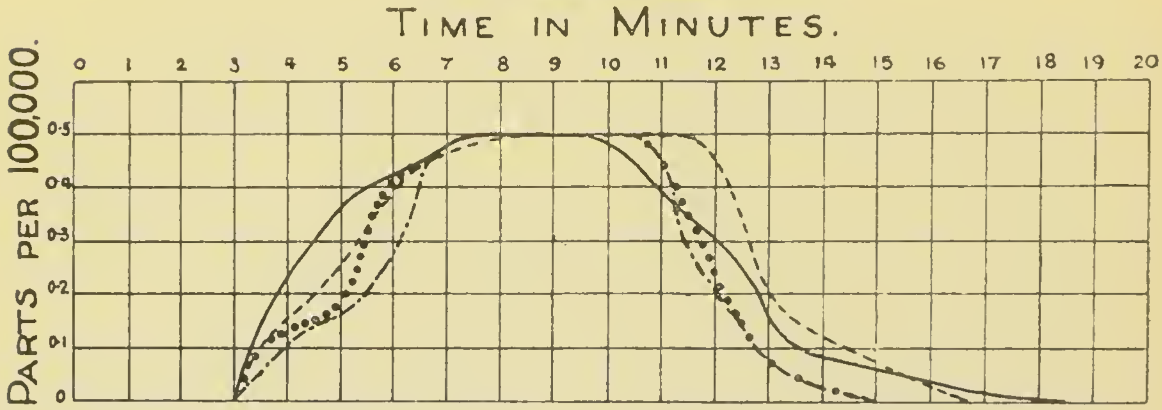
It is impossible to resist the conclusion that, so far as ammonia at least is concerned, no absorption or delay of any kind occurs, but that it is directly oxidized during its passage over the medium, the conversion being practically instantaneous as the ammoniacal nitrogen comes within the grasp of the organisms; and that the nitrogen compounds, gradually changing in character, comport themselves as a whole exactly in this respect as a permanent salt.

It will be objected of course that ammonia is not an organic solid, and, except by extremists, is not to be regarded as subject to absorption.

Precisely similar experiments, however, can be carried out with urea, and with sewage deprived of its suspended solids by filtration through paper.

Table E illustrates the behaviour of these three substances, the solution in each case containing ·5 part of nitrogen per 100,000, and the rate of flow being 10,000 gallons per cubic yard of medium per day of 24 hours.

TABLE E.



Nitric Nitrogen from Ammonium Chloride.----- Chlorine in Sodium Chloride. ———

Nitric Nitrogen from Dissolved Sewage Solids.-·-·-·- Nitric Nitrogen from Urea. ••••••

Rate of flow 10,000 gallons per C. Y. D.

It will be seen that the chlorine in the one case and the nitric nitrogen in the other three appear during the 4th minute, attain the maximum by the 8th minute, and then, the solutions being changed, disappear about the 17th.

It will be readily agreed that, taking the difficulties of the experiment into consideration, the curves are practically indistinguishable, and indeed at a short distance they are inextricable.

It follows that absorption plays no essential part in the oxidation of ammonia, of urea, or of the soluble organic matters of sewage, and that if it occurs in actual sewage treatment at all, of which there is no evidence, it is simply a concurrent phenomenon.

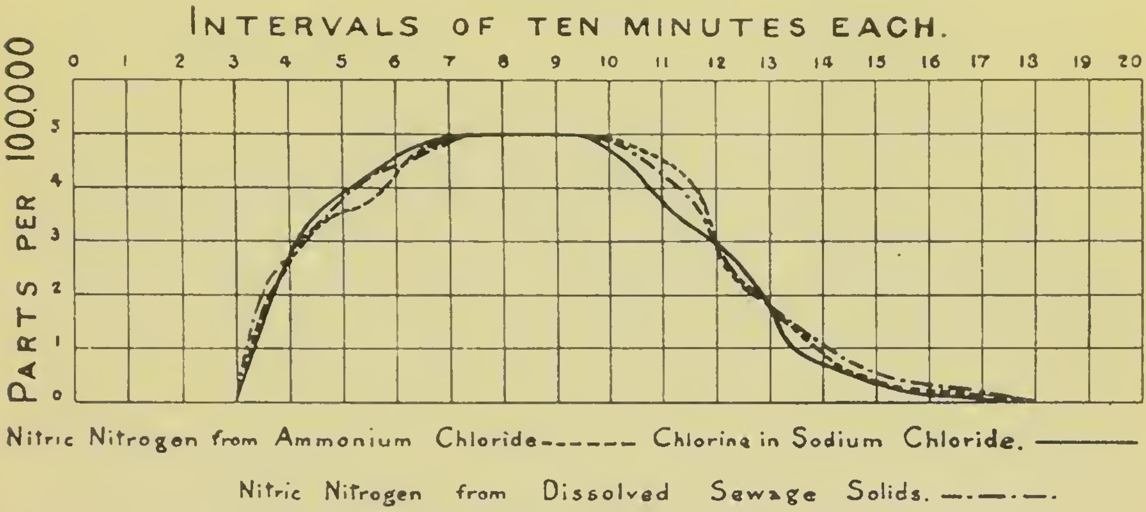
It may be of interest to give the analytical data of the clarified sewage (septic tank effluent) used in the above experiments :—

	Parts per 100,000
Ammoniacal nitrogen	8·4
Albuminoid nitrogen	·90
Total nitrogen (Kjeldahl)	12·20
Colloid do. do.	1·2
Oxygen absorbed in four hours	4·80
Chlorine as chloride	13·0

It will be seen that the liquid used, which was very turbid, was of full strength and normal character ; it was, of course, diluted to the proper strength for the rate of flow, the high rate being chosen not only because the results are condensed within a reasonable period of time, but also because a dropper with a larger orifice can be used with less liability to choking, and because the comparatively large volume of filtrate collected per minute facilitates the tests.

Precisely the same thing occurs, however, at other rates of flow, as shown in Table F, in which the curves show the behaviour of sodium chloride, ammonium chloride, and filtered tank effluent, all containing the chief constituent in the proportion of 5 parts per 100,000, the rate of flow being 1,000 gallons per C.Y.D.

TABLE F.



Rate of flow 1,000 gallons per C.Y.D.

But more than this, typical organic colloids, such as gelatine and albumen, behave in exactly the same way, although, as may be anticipated, it is not possible to completely oxidize the same quantity per cubic yard of filter.

These substances exhibit just the same uninterrupted passage through the filter and the same complete oxidizability during transit as ammonia, and display no greater tendency to linger *en route* than a simple salt such as sodium chloride.

The absorption theory being negatived so directly in this way, it is natural to enquire into the grounds on which that theory can have been so positively advanced.

It has been already shown that the starting-point is the assumption that micro-organisms cannot "decompose highly complex molecules of organic substances within a few minutes, or seconds, with the formation of ammonia and nitrogen gas, and oxidize these substances to nitric acid," etc., and with the exposure of the fallacious nature of this assumption, which may be characterized as an unwarrantable repression of the scientific imagination, the theory itself falls to the ground. But the supporting evidence which has largely assisted in the adoption of the theory merits attention. In the first place, the undoubted reality of absorption phenomena under suitable conditions would seem to constitute an argument in aid, if those conditions could be shown to hold good in the sewage filter; but there is nothing to show that they do exist, at any rate in the more modern continuous form, which is daily displacing the varieties of intermittent filter, and which, whatever its faults may be, exhibits no lack of oxidizing power.

Secondly, that form of absorption associated with the soil has borne an important part in this matter owing to the supposed analogy between the soil and the sewage filter. The points in common are many and important, but the faculty of absorption is especially characteristic of the clays, a type of soil which is probably the most useless of any from the point of view of sewage purification, as is indeed recognized by Dunbar (9).

It is just this property of retention, particularly of ammonia, which makes the clay of so much importance to the agriculturist, whereas the sewage works manager is only too anxious to get rid of his burden if he can do so without offence.

Again, the too limited survey taken by Dunbar of the various means of sewage purification lends an unfounded appearance of soundness to the arguments in favour of absorption.

All his experimental work, highly instructive as it is, appears to have been conducted on the lines of the intermittent filter or of the contact bed; and he has been content to assume that " the results of the Hamburg experiments are of equal scientific and practical importance " to the continuous filter (8). But the differences which exist between these three appliances as regards the relations of the medium, the organisms, the liquid, and the contained air, are very great and important.

There is a certain plausibility, for instance, in the suggestion of absorption in the contact bed which is wholly wanting in the case of the continuous filter.

Moreover, direct experimental evidence of absorption, which should not be difficult to obtain, is almost entirely wanting.

It may be noticed in passing that, as is well known, very elaborate and successful investigations on nitrification have been carried out by Warrington, Munro, and others, by the flask method, in which no solid material was used at all. Unless it is assumed that the walls of the containing vessel afford the necessary surface, we have here numerous cases of nitrification in such various substances as ammonia, urea, asparagine, albumen, ethylamine, gelatine, and thiocyanates, without any possibility of absorption.

What evidence there is of direct fixation of ammonia or nitrogenous colloids by clean sterile materials is curiously conflicting.

Dr. Harriette Chick (10) directly experimented with solution of ammonium chloride on barium sulphate, sand and clinker in fine powder, and with coke in small fragments of 3·5 mm. diameter, all the materials being clean, dry and sterile.

Although in some cases there was a slight loss of nitrogen, the conclusion arrived at was that " there is no evidence of absorption of free and saline ammonia without contemporaneous nitrification."

Fowler (11) has recently repeated and extended these observations, but finds that a very large proportion of the ammonia was fixed, especially by clinker and by a ferruginous gravel; and makes the important note that an appreciable amount of the basic constituents of the material are brought into solution, and that the solvent action is greater with ammonia than when water alone is used.

The writer has repeated these observations, using material exactly similar to that employed in the experimental filters, carefully graded to one-eighth inch, washed, dried, and sterilized.

The solution used contained five parts nitrogen as ammonium chloride per 100,000, and just sufficient was used to cover the material. After standing an hour the ammoniacal nitrogen left in solution was as follows :—

	Original Solution	Marble	Quartz	Clinker
Nitrogen per 100,000 ...	5·0	5·0	5·0	3·35

Whilst, therefore, there was no fixation by the marble or the quartz, the clinker removed one-third of the ammonia.

How is the varied behaviour of these substances to be explained ?

The clue is probably to be found in the chemical interaction between the solution and the medium composed of those substances which do fix ammonia, and which in most if not all cases consist largely of compounds of iron. It is not necessary to assume the direct formation of an insoluble compound, but it is reasonable to explain the position by the formation from the medium, by the direct chemical action of the solution of substances which have a true absorbent power. This would account for the contradictory results obtained by different observers, who, it may be noted, agree when they are dealing with substances of definite chemical composition not attacked by ammonia solution, and not displaying powers of absorption ; but differ when using materials such as clinker, which, though technically classed together, may be substantially different in composition.

The action, whatever it may be, must certainly come to an end early in the life of sewage filters, or the latter would not remain in unimpaired condition for years, as they do, and it must be entirely unimportant in connection with nitrification, for the reason that some of the very best materials for this particular purpose have no power of fixing ammonia at all.

If it be a fact that absorption takes place with one class of material and not at all with another, and if absorption is a necessary preliminary to nitrification, it follows that media of the first class must be pre-eminently suitable as a basis for nitrifying filters. This is certainly not the case.

Then turning to the question of organic solids, Dunbar (12) describes an experiment in which a solution of albumen allowed to remain in contact with sterilized clinker lost 50% within ten minutes, and a further small proportion later.

It has not been found possible to confirm this observation.

A solution of egg albumen, containing about 5 parts of nitrogen per 100,000, was treated exactly as the solution of ammonium chloride in the previous experiment, and it was found that the composition of the liquid remained practically unaltered at the end of the hour, the proportion of nitrogen persisting in the liquid after contact being as follows :—

	Original Solution	Marble	Quartz	Clinker
Nitrogen	5·3	5·3	5·3	5·1

In performing this experiment it is necessary to use a fresh solution of albumen, as if it is allowed to decompose with formation of ammonia, as very readily happens in a warm room, the ammonia may be fixed in contact with the clinker and recorded as albumen.

Is it not again possible that the explanation may be a difference in chemical composition of the clinker, permitting in the one case an alteration which results directly or indirectly in the fixation of the albumen ?

However this may be, the complete nitrification of albumen in a filter composed of marble which shows no power of arresting it, again clearly proves the independence of biological oxidation of any such assistance.

But absorption is said to be a property not of the medium only, but also of the gelatinous coating which generally, though not universally, forms upon the material of a sewage filter.

An experiment by Fowler (13) with ammonium chloride showed a loss of ammonia averaging 2 per cent., i.e., an amount within the limit of experimental error.

The only proof advanced by Dunbar consists of experiments with gases (14)—oxygen and carbon dioxide—and can hardly be said to be conclusive of the absorption of organic substances in solution.

That the sludge deposited within most sewage filters, composed as it is of readily oxidizable substances, should absorb oxygen is not remarkable ; that it should absorb carbon dioxide is not quite so intelligible, and is hardly consistent with the statement (15) that a filter in this condition will continue to *discharge* carbon dioxide " for months."

It must be admitted that direct experimental proof of the simple absorption of such substances by the gelatinous coating would be very difficult if it occurred at all ; but a very convincing if not conclusive argument to the contrary is afforded by the existence of examples of filters with no appreciable coating on the medium at all, but which yet maintain a consistently high level of oxidation. Had such filters, which are generaly fed with chemically precipitated sewage, come within the range of Dunbar's investigations, this part of his argument would have been materially modified. No doubt in these cases the particles of medium must be coated with oxidizing bacteria, but there is no visible gelatinous layer such as could be scraped or washed off, as in the experiments referred to.

A good example may be quoted in the Horfield filter, which for five years, from 1901 to 1906, dealt with the chemically precipitated sewage, amounting to about 50,000 gallons dry weather flow per day, of a suburb of Bristol. The tank effluent was of the ordinary character, and contained quite the usual proportion of suspended solids ; yet when, in consequence of municipal changes, the maintenance of these works became no longer necessary, and the filter was dismantled and transferred to another suburb (where it is now working), the clinker was so clean that, although provision had been made for washing it, no manipulation of any kind was required, and the whole, with the exception of a few cubic feet of material too small for the purpose, was simply carted to the new site.

This consideration leads naturally to the last criticism suggested by the published experiments adduced in support of the absorption theory, namely, that sufficient care has not been taken to discriminate between the dissolved and suspended constituents of sewage. No other interpretation can be placed on the passage last referred to, in which the disengagement of CO_2 for months is mentioned as "showing that the organic carbon of the retained organic matter is converted into CO_2."

It is noticeable that whereas the conclusions formulated upon the experiments are always stated in terms of dissolved organic substances, the liquid experimented upon is generally if not invariably referred to as sewage; though it would be reasonable to expect as a preliminary to all such work a carefully considered description of the way in which substances not in solution were eliminated.

For it is freely admitted that sewage filters of every type intercept and arrest more or less completely solid matters in suspension in the incoming liquid; it is further acknowledged that the suspended matters, especially from septicised sewage, will form a gelatinous coating upon filtering media, and it is not denied, in the entire absence of evidence for or against, that such a coating may exercise some absorbent effect upon the dissolved constituents of the sewage; but the evidence appears to be conclusive that any such absorption, if it occurs at all, exercises no influence upon, and is in no way essential or favourable to, nitrification and allied processes of oxidation of the dissolved constituents.

On the other hand, it would appear reasonable to suspect that the theory of absorption, so far as it relates to the action of sewage filters, originates entirely with the mechanical arrest and subsequent slow decomposition of finely divided organic solids in suspension.

VIII.—Conclusions as to Sewage Disposal.

The experiments detailed above having been set on foot avowedly for the purpose of throwing light upon the changes occurring in the sewage filter, the subject can hardly be left without indicating briefly how far, in the writer's opinion, the results may be applied to the practical operations of treatment.

(*a*). The first and most obvious reflection is that the oxidizable material used has invariably been either a purely artificial solution, more or less representative of the dissolved constituents of sewage, or sewage deprived of its suspended solids.

This is the true function of the sewage filter, so to deal with unstable matters in solution as to render them incapable of such subsequent change as may result in offence to the senses.

The consideration of the undissolved constituents of sewage is beyond the scope of this communication, but in defining the duties of the filter it is necessary to bear in mind that in practice solid deposits found on the area of treatment are of two classes, one consisting of solids entering with the sewage, the other of substances formed, *de novo,* during the process.

In the latter category are solid bodies produced by the chemical interaction of the products of treatment. Ferrous sulphide, for instance, is formed in large quantities in septicised sewage, and is deposited in a gelatinous form which not only occludes the interstices of the filter, and so impedes free aëration, but is fairly permanent.

The object of the preliminary treatment should therefore be twofold, to eliminate the true sewage solids, and to prevent or anticipate the formation of secondary products.

Fortunately, or unfortunately, sewage filters have been found to be capable of supplementing to some extent the action of the tank in intercepting and breaking down undissolved solids, in addition to their proper function of oxidizing dissolved matters, and, on the principle of working the willing horse to death, are not unfrequently encouraged in this course to their detriment.

Two consequences, both of them adverse to the progress of scientific sewage disposal, result from this position. In the first place, it is found to be necessary to construct filters of unduly coarse material in order to accommodate solids which ought never to reach them ; and in the second the need for improvement in the preliminary tank treatment has been obscured.

The production of a perfectly limpid liquid, however putrescible, by the preliminary treatment, is a matter of the greatest importance, and its desirability lends the greatest possible interest to the efforts of the numerous investigators at the present moment engaged in the search for a cheap and effective method.

It has for many years been possible to do all that can be desired in this direction by somewhat expensive chemical manipulations, and it is much to be hoped that some method will be devised of combining this complete defæcation with reasonable economy, as only in this way is it possible to take full advantage of the possibilities of the filter.

(*b*). The method of applying the liquid to the filter adopted in these experiments cannot be utilized on the working scale, but can be very closely imitated by a slight modification in construction.

(*c*). The grade of medium, one-eighth of an inch, is far too small for tank effluents as generally met with, but will be quite practicable when the preliminary treatment has been perfected.

(*d*). The dissolved nitrogenous constituents of sewage can be quantitatively oxidized by treatment on a properly arranged filter ; and the change is a progressive one as the liquid travels over the surface of the medium.

(*e*). The weight of nitrogen, and probably of other elements, that can be oxidized in this way in a given time is practically constant for the same internal filter surface—that is, for the same mass of medium of fixed grade.

The volume of liquid applied to the filter is therefore within wide limits a matter of indifference, a fairly copious dilution seeming rather to favour oxidation.

This principle, which has only of late been recognized by the leading authorities, is of prime importance in connection with sewage disposal, as it leads at once to the conclusion that the extent and therefore the cost of sewage filters may be properly proportioned to the number of contributing persons, and not, as heretofore, to the output of sewage : and going a step farther in the same direction, it is seen that storm water may be effectively treated on the same filtering area as the sewage proper, if means are provided for the removal of the suspended solids.

(*f*). It is of the first importance that the surface and base of the filter should be freely exposed to air ; lateral aëration is not so important.

(*g*). The application of the liquid to the filter should be by drops or very fine streams, and should never be interrupted. An intermission of even ten minutes appreciably reduces the efficiency of the filter, even with so fine a grade of medium as one-eighth of an inch, which naturally equalizes an irregular flow much more completely than a coarser material such as is generally in use. Hence tippers, mechanical sprinklers, and all such appliances as cause interruption in the flow of liquid lower the efficiency of the filter.

(*h*). The liquid should be applied to the medium immediately after comminution to get the maximum effect. It is the more necessary to make this point clear because in a considerable number of instances, particularly in the North of England, the filtering medium has been intentionally placed about two feet below the comminuting apparatus, with the mistaken idea of promoting aëration; but with the inevitable effect of reducing the efficiency of the filter by nearly one-half.

If the object of the filter were merely to dissolve oxygen in the liquid, it is obvious that this would be more completely effected by passing it slowly in thin films over the medium than by rapidly dropping it through the air, a process that has over and over again been shown to be useless; but as the intervention of the micro-organisms is an essential feature of the process, a moment's reflection will show that the medium which is their habitat should receive the liquid at once.

(*i*). Nitrification in ammoniacal solutions is most active at a temperature of 30° C., and falls off both above and below this point. This is also true of sewage filtered from suspended matters.

Experience with crude sewage is not altogether consistent with this observation, for an examination of works during severe cold will generally show that an exceptionally excellent effluent is produced at such times, provided of course that the works are of such a character as not to be mechanically prejudiced by frost.

The explanation is possibly to some extent that the quantity of sewage falls off in severe weather; but some direct experiments on sewage carried out by the author (16) during the severe frost of February, 1902, showed fairly conclusively that the effect of raising the temperature of the incoming liquid was to diminish the amount of nitrate produced, though the formation of nitrite was not so prejudiced or was even increased; and the inference seems to be that septic changes promoted in the deposited solids at the higher temperature were either inimical to nitrification, or perhaps induced de-nitrification. As the ammonia is never entirely nitrified in practice, the effect of elevation of temperature in presence of ammonia, noted under Section III., also bears on this.

(*j*). It is of the greatest economical importance to make the filter body as deep as constructional conditions and the character of the site permit, for the lessened area required involves a proportionately reduced outlay on the floor, the distributing apparatus and, indeed, on all parts of the filter, not even excepting the medium.

In practice, for mechanical reasons, it would seem prudent not to exceed a depth of twelve feet, but this figure should be approached as nearly as possible.

(*k*). It is not usually necessary to supply bases for the nitric acid formed. Ordinary domestic sewage contains 40 to 50 parts per 100,000 calculated as calcium carbonate, but in addition to this the ammonium carbonate present probably acts as base.

(*l*). Given, then, a completely clarified sewage, by a due regard to the principles here laid down, the volume of liquid applied to each unit of filter area might be vastly augmented.

It is not in general necessary to bring about a formation of more than two parts of nitric nitrogen in average sewage containing from 5 to 7 parts of nitrogen per 100,000 in order to produce a satisfactory effluent; that is to say, that in the process of arriving at this result the liquid is so affected by this and the concomitant changes, as to comply with all modern standards, and to be incapable of causing offence even if undiluted.

On this basis every cubic yard of filter would be capable of dealing with quite 2,000 gallons produced by about 70 persons, in 24 hours, if evenly delivered over that period ; or from half to two-thirds of that quantity under the usual conditions of production.

In support of this view, it may be mentioned that on the working scale, with a coarse 3-inch medium and the practical distributing appliance, a nitrification of from 2 to 3 parts of nitrogen has been easily maintained for months together in ordinary precipitation tank effluent, containing from 10 to 14 parts of solids in suspension, applied at the rate of 600 gallons per cubic yard per 24 hours.

If a better clarification of the sewage had permitted the use of a finer grade of medium, there is no doubt that the amount of sewage indicated by the laboratory experiments might have been closely approached.

In conclusion, the writer wishes to acknowledge the valuable assistance Mr. Harold F. Barke, F.I.C., has rendered by executing the very numerous analyses required, and by offering many useful suggestions in the course of the work.

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